

AP3 Rec'd PCT/PTO 05 JUN 2005

1 Improved Vertical External Cavity Surface Emitting Laser

2

3 The present invention relates to an improved Vertical
4 External Cavity Surface Emitting Laser (VECSEL) and in
5 particular to a VECSEL that exhibits improved wavelength
6 tuning characteristics.

7

8 Diode-pumped and electrically pumped VECSELs are an
9 attractive format of semiconductor laser known to those
10 skilled in the art for scientific, instrumentation and
11 non-linear optics applications. The design and
12 fabrication of a VECSEL laser with Circular TEM₀₀ output
13 beams has been described by Kusnetsov et al (IEEE Journal
14 of selected Topics in Quantum Electronics Vol. 5, Page
15 561 - 573 (1999) "Design and Characteristics of High-
16 Power (>0.5W CW) Diode-Pumped Vertical-External-Cavity
17 Surface- Emitting Semiconductor Lasers with Circular TEM₀₀
18 Beams").

19

20 The optical gain medium within a VECSEL is provided by
21 the recombination of electrical carriers within very thin
22 layers of a semiconductor material. These layers are
23 generally termed quantum-well (QW) layers or active

1 layers exhibiting a typical thickness of around 150 Å or
2 less.

3
4 Application of intracavity spectral and temporal control
5 techniques such as picosecond and subpicosecond mode-
6 locking, single-frequency operation and intracavity
7 second-harmonic generation have also been demonstrated
8 see:

- 9 • Garnache et al. Appl. Phys. Lett. Vol 80 Page 3892-3894
10 (2002) "Sub 500-fs Soliton-Like Pulse in a Passively
11 Mode-Locked Broadband Surface-Emitting Laser with 100mW
12 Average Power";
- 13 • Holm et al. IEEE Photon. Technol. Lett. Vol 11 Page
14 1551-1553 (1999) "Actively stabilised Single-Frequency
15 Vertical-Cavity AlGaAs Laser"; and
- 16 • Schiehlen et al. IEEE Photon. Technol. Lett. Vol 14
17 Page 777-779 (2002) "Diode-Pumped Semiconductor Disk
18 Laser With Intracavity Frequency Doubling using Lithium
19 Triborate (LBO)", respectively.

20
21 A significant limiting factor in all of the
22 aforementioned systems is that their output power is
23 greatly limited by the thermal response of the gain
24 medium. Typically, without employing thermoelectric
25 cooler (TEC) mounting techniques or cooling strategically
26 deployed heat sinks with chilled water, both of which are
27 well known to those skilled in the art, the output powers
28 at room temperatures are limited to a few 10's of mW.
29 The employment of these cooling methods act to improve
30 the output powers but are generally very inefficient due
31 to the fact that the heat must be removed from the gain
32 medium via the substrate of the structure.

33

1 The prior art teaches of several methods for improving
2 the efficiency of VECSEL cooling systems. The first
3 involves growing the gain structure in reverse order,
4 mounting on a heatsink and etching away the substrate.
5 However, the resultant scattering due to poor surface
6 quality remains a significant problematic feature within
7 low gain lasers that usually tolerate only very little
8 losses (~4%).

9
10 Alford et al. described an alternative method for
11 removing heat from the gain region that involves no post-
12 growth alterations to the structure (see J. Opt. Soc. Am.
13 B Vol. 19, Page 663 (2002) "*High Power and Good Beam*
14 *Quality at 980nm from a Vertical External-Cavity Surface-*
15 *Emitting Laser*"). In particular this document teaches of
16 an InGaAs-based VECSEL that employs, in conjunction with
17 a thermoelectric cooler, a sapphire heatspreader
18 capillary bonded in optical contact with the epi-side (or
19 active surface) of the gain structure. More recently,
20 Hastie et al. have described a VECSEL that employs an
21 intracavity Silicon Carbide (SiC) heatspreader that is
22 optically contacted to the active surface of the gain
23 medium (see IEEE Photon. Technol. Lett. Vol 15 Page 894-
24 896 (2003) "*0.5 W Single Transverse-Mode Operation of an*
25 *850nm Diode Pumped Surface-Emitting Semiconductor*
26 *Laser*"). Generally, Silicon Carbide has been shown to
27 exhibit superior heat spreading characteristics than
28 heatspreaders comprising Sapphire.

29
30 In order to produce single frequency operation it is
31 known to those skilled in the art to incorporate
32 intracavity polarisation selecting elements such as
33 birefringent filters, orientated at Brewster's angle, and

1 an etalon within the laser cavity. Wavelength scanning
2 can then be achieved via a number of known techniques
3 e.g. the incorporation of stabilisation to a side of a
4 transmission peak of an external reference cavity. Such
5 techniques are currently employed to produce tuneable
6 Ti:Sapphire and Dye lasers that find particular
7 application in the field of high resolution spectroscopy.

8
9 It is known that the gain medium of a VECSEL possesses a
10 relatively high gain bandwidth that provides the
11 potential for a VECSEL to be tuned approximately 20 nm
12 either side of the engineered wavelength. However, in
13 practice it has been found that the above laser frequency
14 stabilisation and wavelength scanning techniques do not
15 lend themselves to be readily incorporated within the
16 described VECSELS. This is principally due to the fact
17 that there is significant modulation of the output power
18 of the VECSEL as the laser's operating wavelength is
19 scanned (between 10 - 30%) due to the heatspreader acting
20 as an additional intracavity etalon. Furthermore, both
21 Sapphire and Silicon Carbide heat spreading elements are
22 found to interfere with the polarisation selection
23 properties of any intracavity birefringent filter thus
24 reducing the frequency stability and tuneability of the
25 cavity.

26
27 It is an object of aspects of the present invention to
28 provide a Vertical External Cavity Surface Emitting Laser
29 (VECSEL) that overcomes one or more of the limiting
30 features on frequency stability and frequency tuning
31 associated with the VECSELS described in the prior art.

32

1 According to a first aspect of the present invention
2 there is provided a Vertical External Cavity Surface
3 Emitting Laser comprising: a semiconductor wafer
4 structure, containing a gain medium and a Bragg
5 reflecting region; and a heatspreader associated with the
6 wafer structure such that the gain medium is located
7 between the heatspreader and the Bragg reflecting region,
8 wherein the heatspreader comprises a non-birefringent
9 material.

10

11 Preferably the heatspreader comprises a first surface
12 upon which is located an anti-reflection coating.

13

14 According to a second aspect of the present invention
15 there is provided a Vertical External Cavity Surface
16 Emitting Laser comprising: a semiconductor wafer
17 structure containing a gain medium and a Bragg reflecting
18 region; and a heatspreader associated with the wafer
19 structure such that the gain medium between is located
20 between the heatspreader and the Bragg reflecting region,
21 wherein the heatspreader comprises a first surface upon
22 which is located an anti-reflection coating.

23

24 Most preferably the heatspreader comprises a non-
25 birefringent material.

26

27 According to a third aspect of the present invention
28 there is provided a Vertical External Cavity Surface
29 Emitting Laser comprising: a semiconductor wafer
30 structure containing a gain medium and a Bragg reflecting
31 region; and a heatspreader associated with the wafer
32 structure such that the gain medium is located between
33 the heatspreader and the Bragg reflecting region, wherein

1 the heatspreader comprises a non-birefringent material
2 and a first surface upon which is located an anti-
3 reflection coating.

4

5 Preferably the anti-reflection coating is optimised for
6 efficient operation with a refractive index of the non-
7 birefringent material and a lasing frequency of the
8 laser.

9

10 Preferably the first surface of the heatspreader comprise
11 a wedge.

12

13 Most preferably the heatspreader comprises a single
14 diamond crystal.

15

16 Optionally lasing of the Vertical External Cavity Surface
17 Emitting Laser is achieved by optical excitement of the
18 gain medium. Alternatively, lasing of the Vertical
19 External Cavity Surface Emitting Laser is achieved by
20 electrical excitement of the gain medium.

21

22 Preferably the laser further comprises an intracavity
23 polarisation selecting element that provides a first
24 means for selecting the operating frequency of the laser.

25

26 Preferably the intracavity polarisation selecting element
27 comprises a birefringent filter orientated at Brewster's
28 angle.

29

30 Preferably the laser further comprises an intracavity
31 etalon that provides a second means for selecting the
32 operating frequency of the laser.

33

1 Preferably the laser further comprises an external
2 reference cavity that allows for the frequency
3 stabilisation of the laser output to a side of a
4 transmission peak of the external cavity.

5

6 Optionally the laser comprises a three mirror folded
7 cavity arrangement.

8

9 Preferably the laser further comprises a cavity mirror
10 mounted on a first piezoelectric crystal and an output
11 coupler mounted on a second piezoelectric crystal wherein
12 the combined movement of the cavity mirror and the output
13 coupler provides a first means for frequency tuning the
14 output of the laser.

15

16 Alternatively, the laser further comprises a pair of
17 Brewster plates and a cavity mirror mounted on a
18 piezoelectric crystal wherein the combined movement of
19 the Brewster plates and the cavity mirror provide a
20 second means for frequency tuning the output of the
21 laser.

22

23 According to a fourth aspect of the present invention
24 there is provided a frequency scanning Vertical External
25 Cavity Surface Emitting Laser suitable for use in high
26 resolution spectroscopy experiments comprising: apparatus
27 for selecting and stabilising the operating frequency of
28 the laser; apparatus for scanning the operating frequency
29 of the laser; a semiconductor wafer structure containing
30 a gain medium and a Bragg reflecting region; and a
31 heatspreader associated with the wafer structure such
32 that the gain medium is located between the heatspreader

1 and the Bragg reflecting region, wherein the heatspreader
2 comprises a non-birefringent material..

3
4 Preferably the heatspreader comprises a first surface
5 upon which is located an anti-reflection coating.

6
7 Preferably the apparatus for selecting and stabilising
8 the operating frequency of the laser comprises an
9 intracavity polarisation selecting element that provides
10 a first means for selecting the operating frequency of
11 the laser.

12
13 Optionally the apparatus for selecting and stabilising
14 the operating frequency of the laser further comprises an
15 intracavity etalon that provides a second means for
16 selecting the operating frequency of the laser.

17
18 Optionally the apparatus for selecting and stabilising
19 the operating frequency of the laser further comprises an
20 external reference cavity that allows for the frequency
21 stabilisation of the laser output to a side of a
22 transmission peak of the external cavity.

23
24 Preferably the apparatus for scanning the operating
25 frequency of the laser comprises a cavity mirror mounted
26 on a first piezoelectric crystal and an output coupler
27 mounted on a second piezoelectric crystal wherein the
28 combined movement of the cavity mirror and the output
29 coupler provides a first means for frequency tuning the
30 output of the laser.

31
32 Alternatively, the apparatus for scanning the operating
33 frequency of the laser comprises a pair of Brewster

1 plates and a cavity mirror mounted on a piezoelectric
2 crystal wherein the combined movement of the Brewster
3 plates and the cavity mirror provides a second means for
4 frequency tuning the output of the laser.

5
6 Preferably the anti-reflection coating is optimised for
7 efficient operation with a refractive index of the non-
8 birefringent material and a lasing frequency of the
9 laser.

10
11 Preferably the first surface of the heatspreader comprise
12 a wedge.

13
14 Most preferably the heatspreader comprises a single
15 diamond crystal.

16
17 Aspects and advantages of the present invention will
18 become apparent upon reading the following detailed
19 description and upon reference to the following drawings
20 in which:

21
22 Figure 1 presents a schematic representation of an
23 improved Vertical External Cavity Surface
24 Emitting Laser (VECSEL) that incorporates
25 intracavity elements for single frequency
26 selection;

27
28 Figure 2 presents:

29 (a) a schematic representation; and

30 (b) a schematic bandgap diagram,

31 of the gain medium of a 980 nm VECSEL of
32 Figure 1;

33

1 Figure 3 presents further detail of the cooling
2 apparatus and a heatspreader employed by the
3 VECSEL of Figure 1;

4

5 Figure 4 presents an output power curve, as a function
6 of pump power, for the VECSEL of Figure 1
7 designed to operate around a 980 nm central
8 output wavelength;

9

10 Figure 5 presents a measured residual frequency noise
11 output for the 980 nm VECSEL of Figure 1;

12

13 Figure 6 presents a measured wavelength tuning curve for
14 the 980 nm VECSEL of Figure 1 when coupled to a
15 transmission peak of an external reference
16 cavity; and

17

18 FIGURE 7 presents schematic detail of:

- 19 (a) an on axis back pumped VECSEL;
20 (b) an on axis back pumped VECSEL that
21 incorporates a second heatspreader; and
22 (c) an off-axis back pumped VECSEL;
23 in accordance with various aspects of the
24 present invention.

25

26 Referring to Figure 1 a schematic representation of a
27 Vertical External Cavity Surface Emitting Laser (VECSEL)
28 1, in accordance with an aspect of the present invention
29 is provided. The VECSEL 1 can be seen to comprise a
30 semiconductor wafer structure 2 mounted within a cooling
31 apparatus 3 that is located within a three mirror folded
32 cavity arrangement.

33

1 A first mirror within the cavity arrangement comprises a
2 Bragg reflector region 4 integrated within the wafer
3 structure 2 (further details of which are outlined
4 below). A second mirror comprises a standard curved
5 cavity mirror 5 mounted on a first piezoelectric crystal
6 6 so allowing for fine adjustment of the length of the
7 cavity. An output coupler 7, mounted on a second
8 piezoelectric crystal 8 so allowing for coarse adjustment
9 of the length of the cavity, is then employed as the
10 third cavity mirror. Between the curved cavity mirror 5
11 and the output coupler 7 are located a birefringent
12 filter 9 employed to provide coarse frequency selection
13 within the cavity and a solid etalon 10 employed for fine
14 frequency selection of the operating wavelength. The
15 wafer structure 2 is optically pumped by initially
16 coupling the output of a pump laser source (not shown)
17 into an optical fibre 11. Thereafter, the coupled pump
18 laser output is focussed via two input lens elements 12
19 onto the wafer structure 2.

20

21 A schematic representation of the wafer structure 2 is
22 presented in Figure 2(a). The wafer structure 2 is grown
23 by a metal-organic chemical vapour deposition (MOCVD)
24 technique on a 2 inch (5.08 cm) 500 mm thick (001) GaAs
25 substrate 13. The wafer structure 2 comprises a single
26 distributed Bragg reflector region 4, a gain medium 14, a
27 carrier confinement potential barrier 15 and an oxidation
28 prevention layer 16.

29

30 The Bragg reflector region 4 comprises thirty pairs of
31 AlAs-GaAs quarter-wave layers that exhibit a total
32 reflectivity greater than 99.9% centred at 980 nm while
33 the carrier confinement potential barrier comprises a

1 single wavelength-thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer. The oxidation
2 prevention layer comprises a thin $\text{In}_{0.48}\text{Ga}_{0.52}\text{P}$ cap.

3

4 The gain medium 14 comprises twelve 6 nm thick $\text{In}_{0.16}\text{GaAs}$
5 quantum wells equally spaced between half-wave
6 $\text{Al}_{0.06}\text{Ga}_{0.8}\text{As}/\text{GaAsP}$ structures that allow the VECSEL 1 to be
7 optically pumped at 808 nm while generating an output in
8 the range of 970 - 995 nm. (referred to below as the 980
9 nm VECSEL)

10

11 A schematic representation of the lasing mechanism is
12 presented in the bandgap diagram of Figure 2(b). The
13 pump field 17 is absorbed in the barrier regions and
14 carriers thereafter diffuse into the quantum wells so as
15 to produce the required population inversion for lasing
16 to take place.

17

18 Figure 3 presents further detail of the cooling apparatus
19 3 and heatspreader 18 employed in order to improve the
20 operating characteristics of the VECSEL 1. In particular
21 the cooling apparatus 3 comprises a standard
22 thermoelectric cooler 19 while the heat spreader 18
23 comprises a single diamond crystal that comprises an
24 external, wedged face 20. A high performance anti-
25 reflection coating is deposited on the surface of the
26 wedged face 20.

27

28 The single diamond crystal heatspreader 18 is bonded in
29 optical contact with the wafer structure 2 so that the
30 gain medium 14 is located between the heatspreader 18 and
31 the Bragg reflector region 4. The wafer structure 2 and
32 heatspreader 18 are then clamped on top of a layer of
33 indium foil 21 onto the thermoelectric cooler 19.

1
2 Single diamond crystal is suited to be employed as the
3 heatspreader 18 since it exhibits comparable thermal
4 conductivity levels as Sapphire and Silicon Carbide.
5 Thus, the described arrangement allows the heatspreader
6 18 to immediately spread the heat generated within the
7 gain medium 14 by the pump field 17 to the cooling
8 apparatus 3 after it has propagated only a limited
9 distance into the gain medium 14, so significantly
10 increasing the efficiency of the device. In addition
11 there are further inherent advantages of employing the
12 single diamond crystal as the heatspreader 18 over those
13 described in the prior art. These reside in the fact
14 that the single diamond crystal is non-birefringent. As
15 such the presence of the heatspreader 18 no longer
16 interferes with polarisation selecting properties of the
17 birefringent filter 9 and so there are no additional
18 intracavity losses experienced on the output of the
19 VECSEL 1 as the laser is tuned (see Figure 6 below).
20
21 The lack of birefringence within the heatspreader 18 also
22 allows for an optimised anti-reflection coating to be
23 applied to the surface of the wedged face 20. It is
24 known to those skilled in the art that in order to
25 optimise an anti-reflection coating it is necessary that
26 the refractive index of the medium to which the coating
27 is to be applied is known to a high degree of accuracy.
28 Therefore, if the heatspreader 18 were to exhibit
29 birefringence (as is the case for Sapphire and Silicon
30 Carbide) two effective refractive indices would be
31 present. A direct result of this is that the effective
32 refractive index experienced by a propagating optical
33 field of a fixed polarisation would be critically

1 dependent on the orientation of the heatspreader 18
2 within the VECSEL 1, restricting alignment to a single
3 orientation only. Practically this would significantly
4 complicate the already difficult cavity alignment
5 process.

6
7 However, this is not the case with the single diamond
8 crystal heatspreader 18 thus permitting the incorporation
9 of the anti-reflection coating. The anti-reflection
10 coating acts to significantly reduces the power
11 modulation effects, caused by the presence of the
12 intracavity heatspreader 18, experienced when the 980 nm
13 VECSEL is wavelength tuned (see Figure 6 below).

14
15 Figure 4 provide some typical operational characteristics
16 of the described VECSEL 1 systems in the absence of the
17 birefringent filter 9 and the solid etalon 10. In
18 particular Figure 4 presents the 980 nm VECSEL output
19 power as a function of pump power, when the heatsink
20 temperature was maintained at 10°C. The pump power was
21 provided by a commercially available 200 µm fibre coupled
22 laser that generated a 25 W pump field at 808 nm. A 2%
23 output coupler 7 was employed so producing a maximum
24 output power of 1.75 W in a TEM₀₀ mode with 6.2 W of pump
25 power.

26
27 On introducing the birefringent filter 9, the solid
28 etalon 10 and a 1% output coupler 7 to the cavity it is
29 possible to stabilise the output frequency of the device
30 to the side of a transmission peak of an external
31 reference cavity (not shown). The operational
32 characteristics of the 980nm VECSEL are shown in
33 Figure 5. The VECSEL 1 can be seen to operate at a

1 single frequency exhibiting a residual frequency
2 fluctuation amounting to a linewidth of around 85 kHz
3 r.m.s.
4

5 By employing the first 6 and second piezoelectric
6 crystals 8 the curved cavity mirror 5 and the output
7 coupler 7, respectively, can be translated so as to allow
8 for the tuning of the output wavelength of the VECSEL 1.
9 A typical tuning curve for the 980nm VECSEL is presented
10 in Figure 6. It should be noted that the modulation in
11 the output power can be seen to have been reduced to less
12 than 5%.
13

14 An alternative means for tuning the laser cavity
15 comprises the introduction of a pair of Brewster plates
16 (not shown) into the laser cavity. When the orientation
17 of the Brewster plates are rotated in conjunction with
18 the translational movement of the curved cavity 5 mirror
19 mounted on the piezoelectric crystal 6 the output
20 wavelength of the laser can be scanned, as is known to
21 those skilled in the art.
22

23 As will be apparent to those skilled in the art
24 alternative semiconductor wafer structures 2 may be
25 incorporated within the VECSEL 1 in order to provide
26 different operating wavelength ranges. Furthermore, the
27 VECSEL outlined above has been described in relation to a
28 three mirror folded cavity chosen for ease of
29 engineering. However, it will again be readily apparent
30 to those skilled in the art that alternative cavity
31 arrangements may be employed without departing from the
32 scope of the invention. For example the laser cavity may

1 be established between the Bragg reflector 4 and a curved
2 output coupler 7.

3

4 In alternative embodiments of the VECSEL the gain medium
5 14 can be back pumped by arranging the optical pump field
6 17 to be initially incident on the Bragg reflector region
7 4 of the semiconductor wafer structure 2, see Figure 7.

8

9 In particular Figure 7(a) presents a schematic
10 representation of an on axis back pumped VECSEL 22. In
11 this embodiment the wafer structure 2 and the
12 heatspreader 18 are located within a mount 23 formed from
13 a high thermally conductive material e.g. copper. The
14 location of the heatspreader 18 and the wafer structure 2
15 may be achieved in a number of ways including simply
16 mechanically clamping the heatspreader 18 within the
17 mount 23 with a retaining flange 24, and/or bonding or
18 soldering the heatspreader 18 to the mount 23 and/or by
19 incorporating tapered edges on both the heatspreader 18
20 and the mount 23 so as to create a compression fit
21 between these components. Suitable materials for
22 producing the retaining flange include copper, as per the
23 present embodiment, or Chemical Vapour Deposition (CVD)
24 diamond.

25

26 An aperture 25 is located within the retaining flange 24
27 so as to allow the pump field 17, provided by the optical
28 fibre 11, to be focused by a lens 26 so as to achieve the
29 required spot size within the gain medium 14. The design
30 of the GaAs substrate 13 and the Bragg reflector region 4
31 is such that they are substantially transparent to the
32 pump field 17. Propagation of the pump field 17 through
33 the GaAs substrate 13 can be enhanced by introducing an

1 anti-reflection coating optimised for the wavelength of
2 the pump field 17.

3

4 In an alternative embodiment of the on axis back pumped
5 VECSEL (not shown) the lens 26 is removed and the optical
6 fibre is abutted directly against the wafer structure 2
7 via the aperture 25.

8

9 Figure 7(b) presents a schematic representation of an
10 alternative on axis back pumped VECSEL 27. In this
11 arrangement the GaAs substrate 13 has been removed from
12 the semiconductor wafer structure 2 so as to expose the
13 Bragg reflecting region 4. The removal of the GaAs
14 substrate 13 can be simply achieved mechanically or by
15 etching methods, techniques that are already known to
16 those skilled in the art.

17

18 Removal of the GaAs substrate 13 has several advantages.
19 In the first instance it reduces the wavelength
20 restrictions on the pump field 17 as it is now only
21 required to propagate through the Bragg reflecting region
22 4 before being absorbed within the gain medium 14.
23 Secondly, the removal of the GaAs substrate 13 also
24 allows for the incorporation of a second heatspreader 28
25 that is located in thermal contact with the Bragg
26 reflecting region 4, as shown schematically in Figure
27 7(b). This arrangement allows for additional improvement
28 of the operating characteristics of the VECSEL 27. As
29 the second heatspreader 28 is not an intra cavity element
30 the optical criteria placed on this component are
31 significantly reduced when compared with the intra cavity
32 heatspreader 18. Indeed this component can be made from
33 any material that is optically transparent to the pump

1 field and which exhibits good thermal conductivity
2 properties e.g. diamond, sapphire, Silicon Carbide, CVD
3 diamond and glass.

4

5 Figure 7(c) presents a schematic representation of a yet
6 alternative embodiment of the present invention, namely
7 an off-axis back pumped VECSEL 29. In this embodiment an
8 off axis pump field 17 is directed so as to back pump the
9 gain medium, in a similar manner to that described above,
10 through the employment of an off axis arrangement of the
11 optical fibre 11 and lens 26, as shown. An additional
12 intra cavity mirror 30, coated so as to efficiently
13 reflect the pump field 17, is then employed so as to
14 retro reflect any of the pump field 17 not absorbed on
15 the initial pass through the gain medium 14. With this
16 embodiment the efficiency of the absorption of the pump
17 field 17 within the gain medium 14 is increased so
18 improving the overall efficiency of the VECSEL 29.

19

20 It will be appreciated by those skilled in the art that
21 the advantages of the additional intra cavity mirror 30
22 can be harnessed within an on axis embodiment if this
23 mirror is suitably coated so as to reflect light at the
24 wavelength of both the pump field 17 and the VECSEL
25 operating wavelength. With this arrangement the intra
26 cavity mirror 30 thus functions to reflect any unabsorbed
27 pump field 17 back towards the gain medium 14 as
28 previously described, as well as acting as a normal
29 cavity mirror.

30

31 The above described VECSELS have all been described in
32 relation to optically pumped systems. However, it will
33 be appreciated by those skilled in the art that the

1 advantages of the heatspreader 18 can readily be
2 incorporated within an electrically pumped VECSEL systems
3 where the electrical contacts are arranged in such a
4 manner so as to allow the heatspreader 18 to be located
5 with gain medium 14.

6
7 The VECSELs described above all employ a non-birefringent
8 heatspreader that allows the full tuning potential of the
9 associated gain medium to be exploited. Single diamond
10 crystal is employed as the heatspreader since it provides
11 the required level of thermal conductivity so as to act
12 as an efficient heatspreader. The fact that the
13 heatspreader is non-birefringent means that there is no
14 detrimental interaction between the heatspreader and the
15 polarisation selecting properties of an intracavity
16 birefringent filter employed for coarse frequency
17 selection within the cavity. Furthermore, the fact that
18 heatspreader is non-birefringent allows the application
19 of an optimised anti-reflection coating to a surface of
20 the heatspreader so as to significantly reduce the
21 modulation on the output power experienced by prior art
22 systems. This modulation of the output power can be
23 further reduced by arranging that the surface to which
24 the anti-reflection coating is applied is substantially
25 wedged.

26
27 The foregoing description of the invention has been
28 presented for purposes of illustration and description
29 and is not intended to be exhaustive or to limit the
30 invention to the precise form disclosed. The described
31 embodiments were chosen and described in order to best
32 explain the principles of the invention and its practical
33 application to thereby enable others skilled in the art

1 to best utilise the invention in various embodiments and
2 with various modifications as are suited to the
3 particular use contemplated. Therefore, further
4 modifications or improvements may be incorporated without
5 departing from the scope of the invention herein
6 intended.

7